Electronic Version

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Description

LINEAR DECIBEL-SCALE VARIABLE GAIN AMPLIFIER

CROSS REFERENCE TO RELATED APPLICATIONS

[0001] This application is a continuation-in-part of application of U.S. Serial Number 10/708202 filed on Feb. 16, 2004, which is still pending. This application is related to a co-pending application "LINEAR-IN-DECIBEL VARIABLE GAIN AMPLIFIER"which belongs to the same assignee and filed on the same day with this application.

BACKGROUND OF INVENTION

[0002] 1. Field of the Invention

[0003] The invention relates to a variable gain amplifier, and more particularly, to a variable gain amplifier having a linear decibel-scale gain with respect to the controlling voltage(s).

[0004] 2. Description of the Prior Art

[0005] Wireless communication system development continues to

rapidly progress. As a result, many types of high bandwidth high sensitivity transceivers have been proposed. Variable gain amplifiers are often used in these types of transceiver to broaden the processing range of the system. A variable gain amplifier having a linear gain in the decibel (dB) scale with respect to the controlling voltage(s) has the broadest gain range.

[0006] Please refer to Fig.1, where a circuit diagram of a conventional variable gain amplifier is illustrated. The variable gain amplifier shown in Fig.1 is a differential amplifier. The voltage gain Av of the variable gain amplifier can be determined from the half circuit of the differential amplifier. Disregarding the phase, the voltage gain Av of this variable gain amplifier is:

[0007]

$$Av = \frac{Vout}{Vin} = \frac{K}{1 + \exp(\frac{Vy}{Vt})}$$

(1)

[0008] where K is substantially a constant.

[0009] From equation 1 it can be seen that the denominator of

the voltage gain Av is not a simple exponential function that it has a constant term "1" in addition to the simple exponential function exp(Vy/Vt). Consequently, the voltage gain Av does not have a simple exponential relationship with the controlling voltage Vy.

[0010] Please refer to Fig.2. Fig.2 is a graph showing the relationship between the voltage gain Av and the controlling voltage Vy of Fig.1. Note that when Vy < Vt, the voltage gain Av does not change exponentially with respect to the change in the controlling voltage Vy. The smaller the controlling voltage Vy, the less the voltage gain Av changes with respect to the change in the controlling voltage Vy. The area where the voltage gain Av does not have a perfect exponential relationship with the controlling voltage Vy is caused by the constant term 1 in the denominator of equation 1.

[0011] Furthermore, equation 1 contains a term called the thermal voltage Vt, which is a variable that changes in response to the change of temperature. The result is that the relationship between the voltage gain Av and the controlling voltage Vy does not remain constant when temperature changes.

SUMMARY OF INVENTION

[0012] It is therefore one of the objects of the claimed invention to provide a variable gain amplifier having a linear voltage gain in the decibel-scale with respect to the controlling voltage(s) and which will not be influenced by changes in temperature, to solve the above-mentioned problems.

[0013] According to the disclosed embodiment, a variable gain amplifier comprising: an amplifying stage and a gain controlling stage. The amplifying stage is for generating an output voltage according to a differential input voltage. The gain controlling stage is for adjusting a voltage gain of the amplifying stage according to a first controlling voltage and a second controlling voltage. The gain controlling stage comprising a proportional_to_Vt voltage amplifier, a transconductance unit, a first current transforming unit, a second current transforming unit and an output unit. The gain controlling stage can generate a gain controlling voltage to control the voltage gain of the amplifying stage according to the first controlling voltage and the second controlling voltage.

[0014] These and other objectives of the present invention will no doubt become obvious to those of ordinary skill in the art after reading the following detailed description of the preferred embodiment that is illustrated in the various fig-

ures and drawings.

Brief Description of Drawings

[0015] Fig.1 is a circuit diagram of a conventional variable gain amplifier.

[0016] Fig.2 is a graph showing the relationship between the voltage gain Av and the controlling voltage Vy of Fig.1.

[0017] Fig.3 is a diagram of a variable gain amplifier according to the present invention.

[0018] Fig.4 and Fig.5 are circuit diagrams of the gain controlling stage of Fig.3.

[0019] Fig.6 is a graph showing the relationship between the voltage gain Av and the difference between the first and the second controlling voltages according to equation 11.

[0020] Fig.7 is a diagram of a proportional_to_Vt voltage amplifier according to the present invention.

Detailed Description

[0021] Please refer to Fig.3 showing a schematic diagram of a variable gain amplifier 300 according to the embodiment of the present invention. The variable gain amplifier 300 comprises an amplifying stage 302 for generating an output voltage Vout according to an input voltage Vin and a gain controlling voltage V_y. A voltage gain, i.e. the ratio

between the output voltage Vout and the input voltage Vin, is determined by the gain controlling voltage V_y. A gain controlling stage 304 is for generating the gain controlling voltage Vy.

[0022] In this embodiment, the amplifying stage 302 is substantially the same as the variable gain amplifier shown in Fig. 1. Concerning the amplifying stage 302 please refer to Fig.1 and the above description describing the variable gain amplifier shown in Fig.1. Referring to equation 1, it can be seen that the value of the voltage gain of the amplifying stage 302 is determined by the gain controlling voltage Vy.

[0023] Next, please refer to Fig.4 and Fig.5, where circuit diagrams of the gain controlling stage 304 according to the embodiment of the present invention are illustrated. The gain controlling stage 304 is for determining the value of the gain controlling voltage Vy output to the amplifying stage 302 according to a first controlling voltage V1 and a second controlling voltage V2. In this embodiment, the gain controlling stage 304 comprises a proportional_to_Vt voltage amplifier 400, a transconductance unit 401, a first current transforming unit 403, a second current transforming unit 405 (as shown in Fig.4), and an outputting

unit 407 (as shown in Fig.5).

[0024] The proportional_to_Vt voltage amplifier 400 is for generating a third controlling voltage V3 and a fourth controlling voltage V4 according to V1 and V2, wherein the difference (V4-V3) is proportional to the thermal voltage Vt and the difference (V2-V1). The operation of the proportional_to_Vt voltage amplifier 400 will be -explained later in this description.

[0025] The transconductance unit 401 comprises a first transistor 472 coupled to the third controlling voltage V3, a second transistor 473 coupled to the fourth controlling voltage V4, a first bias current source Ibias1 coupled to the emitter of the first transistor 472 and the emitter of the second transistor 473 for providing a first bias current Ibias1, a first current source 402, a first resistor R1 coupled between the collector of the first transistor 472 and the first current source 402, and a second resistor R2 coupled between the collector of the second transistor 473 and the first current source 402.

[0026] The value of the first current I1 flowing through the collector of the second transistor 473 is determined by the first bias current Ibias1 and the difference between the third controlling voltage V3 and the fourth controlling

voltage V4. In this embodiment, the relationship is as follows:

[0027]

$$I1 = Ibias1/[1+\exp(\frac{V3-V4}{Vt})]$$

(2)

[0028] Because the transconductance unit 401 is a differential circuit, the collector current of the first transistor 472 is determined by the third controlling voltage V3, the fourth controlling voltage V4, and the first bias current Ibias1. The relationship is similar to that shown in equation 2, only the positions of the terms V3 and V4 are exchanged.

[0029] The first current transforming unit 403 is coupled to the transconductance unit 401 through the second current source 404. The first current transforming unit 403 comprises a third transistor 474 having the collector and the base being coupled together, a fourth transistor 475, a second bias current source Ibias2 coupled to the emitter of the third transistor 474 and the emitter of the fourth transistor 475 for providing a second bias current Ibias2, a second current source 404, a third resistor R3 coupled between the collector of the third transistor 474 and the second current source 404, and a fourth resistor R4 cou-

pled between the collector of the fourth transistor 475 and the second current source 404. The second current source 404 and the first current source 402 form a current mirror circuit. Additionally, in this embodiment, the ratio between the collector current I2 of the third transistor 474 and the collector current I1 of the second transistor 473 is the same as the ratio between the first bias current Ibias1 and the second bias current Ibias2, as follows:

[0030] I2 / I1 = Ibias2 / Ibias1 (3)

[0031] Because the first current transforming unit 403 is also a differential circuit, according to the current relationship shown in equation 3, the ratio between the collector current of the fourth transistor 475 and the collector current I2 of the third transistor 474 is the same as the ratio between the collector current of the first transistor 472 and the collector current I1 of the second transistor 473. In this embodiment, when the first bias current Ibias1 equals the second bias current Ibias2, the collector current of the first transistor 472 will also be equal to the collector current of the fourth transistor 475, and the collector current I1 of the second transistor will be equal the collector current I2 of the third transistor.

[0032] The second current transforming unit 405 comprises a

fifth transistor 476 having the base and the collector coupled to the base of the fourth transistor 475, a sixth transistor 477 having the base coupled to the base and the collector of the third transistor 474, and a seventh transistor 478 coupled to the emitter of the fifth transistor 476 and the emitter of the sixth transistor 477 for providing a third bias current Ibias3. Due to the loop formed between the third transistor 474, the fourth transistor 475, the fifth transistor 476, and the sixth transistor 477, the ratio between the collector current I3 of the sixth transistor 476 and the collector current I2 of the third transistor 474 is the same as the ratio between the third Ibias2 and the first bias current Ibias1. This is shown in the following equation:

[0033] $I3 / I2 = Ibias3 / Ibias2$ (4)

[0034] The second current transforming unit 405 is also a differential circuit. Similar to the relationship shown in equation 4, the ratio between the collector current I4 of the fifth transistor 476 and the collector current I3 of the sixth transistor 477 is the same as the ratio between the collector current of the fourth transistor 475 and the collector current I2 of the third transistor 474.

[0035] Hence, according to equations 2, 3, 4, and the relation-

ship between I4 and I3 described above, the circuit shown in Fig.4 is a voltage controlled current amplifier. By way of changing the value of the differential input voltage, i.e. the difference between the third controlling voltage V3 and the fourth controlling voltage V4, the ratio between the output currents I3 and I4 is controlled. The ratio is as follows:

[0036]

$$\frac{I4}{I3} = K \cdot \exp\left(\frac{V3 - V4}{Vt}\right)$$

(5)

[0037] The outputting unit 407 shown in Fig.5 comprises a eighth transistor 479 having the base and the collector being coupled together, a ninth transistor 480, and a fourth bias current source I4 coupled to the emitter of the eighth transistor 479 and the emitter of the ninth transistor 480. Please note that the voltage controlled current amplifier shown in Fig.4 is coupled to the outputting unit 407 shown in Fig.5 through at least one current mirror device (not shown), such that the bias current output by the fourth bias current source is substantially the same as the collector current I4 of the fifth transistor 476, and the

collector current I3 of the sixth transistor 477 is substantially the same as the collector current I3 of the eighth transistor 479. Although the current mirrors are not shown, a person skilled in the art can easily design such the at least one current mirror device. At this point, the collector current of the eighth transistor 479 will be equal to the collector current I3 of the sixth transistor 477, and the collector current of the ninth transistor 480 will be equal to the difference between the collector current I4 of the fifth transistor 476 and the collector current I3 of the sixth transistor 477. The base of the eighth transistor 479 and the base of the ninth transistor 480 are for coupling to the amplifying stage 302 and outputting the gain controlling voltage Vy. Hence, the relationship of the gain controlling voltage Vy, the collector current I3 of the eighth transistor 479 and the collector current (I4-I3) of the ninth transistor 480 is follows:

[0038]

$$Vy = Vt \cdot \ln\left(\frac{I4 - I3}{I3}\right) = Vt \cdot \ln\left(\frac{I4}{I3} - 1\right)$$

(6)

[0039] Accordingly, disregarding the proportional_to_Vt voltage amplifier 400, the gain controlling stage 304 is for deter-

mining the current relation in each stage of the differential circuit according to the difference between the third controlling voltage V3 and the fourth controlling voltage V4, and for determining the value of the gain controlling voltage Vy according to these current relationships. Consequently, the relationship between the gain controlling voltage Vy, the third controlling voltage V3, and the fourth controlling voltage V4 is as follows:

[0040]

$$Vy = Vt \cdot \ln[K \cdot \exp(\frac{V3 - V4}{Vt}) - 1]$$

(7)

[0041] Using the gain controlling voltage Vy output by the gain controlling stage 304 as the controlling voltage Vy of the amplifying stage 302 shown in Fig.1, the voltage gain of the amplifying stage 302, i.e. the ratio between the output voltage Vout and the input voltage Vin is as follows:

[0042]

$$Av = \frac{Vout}{Vin} = \frac{K1}{\exp[K2(V3 - V4)]}$$

(8)

[0043] where K1 relates to the output resistance RL of the ampli-

fying stage 302, and K2 relates to the thermal voltage Vt of bipolar junction transistors, i.e. K2 is proportional to 1/Vt. In this embodiment K1 is a constant, however, the value of K2 can be influenced by thermal voltage Vt. In other words, any factor influencing the thermal voltage can change the value of K2.

[0044] Please refer to Fig.7 where an embodiment of the proportional_to_Vt voltage amplifier according to the embodiment of the present invention is illustrated. In Fig.7 the proportional_to_Vt voltage amplifier 700 has a single input end (V1) and a single output end (V3), however, it is also possible to use two amplifiers as shown in Fig.7 to form a differential type proportional_to_Vt voltage amplifier.

[0045] The proportional_to_Vt voltage amplifier 700 contains a transconductance unit 720, a current mirror 740, and a transresistance unit 760. The transconductance unit 720 contains an operational amplifier 721 and a resistor R, for generating a fifth current I5 according to the first controlling voltage V1, wherein I5=V1/R. The current mirror 740 is for generating a sixth current I6 by replicating the fifth current I5. The transresistance unit 760 couples to the current mirror 740 and a reference voltage Vref, compris-

ing a tenth transistor 761, an eleventh transistor 762, and a fourth current source Ibias4. Through the circuit configuration shown in Fig.7, the relationship between the third controlling voltage V3 and the first controlling voltage V1 is as follows:

[0046]

$$V3 - Vref = \frac{V1}{R \cdot Gm}$$

(9)

[0047] where Gm is the transconductance of the transistors 761 and 762. Because Gm=Ic/Vt (in this embodiment Ic is substantially equal to Ibias4 / 2), V1-Vref will be proportional to the thermal voltage Vt. Combining two proportional_to_Vt voltage amplifiers 700 shown in Fig.7 can form a differential proportional_to_Vt voltage amplifier 400 shown in Fig.4, having the relationship between its inputs and outputs be as follows:

[0048]

$$V4 - V3 = K3 \cdot Vt \cdot (V1 - V2)$$

(10)

[0049] With the proportional_to_Vt voltage amplifier 400 combined in the gain controlling stage 304, the voltage gain

Av of the variable gain amplifier 300 will be as follows:

[0050]

$$Av = \frac{Vout}{Vin} = \frac{K1}{\exp\left[K4(V1 - V2)\right]}$$

(11)

[0051] where both K1 and K4 are constants. The result is that the voltage gain Av of the variable gain amplifier 300 has a simple exponential relation with the first controlling voltage V1 and the second controlling voltage V2, and the voltage gain Av will not be affected by the thermal voltage.

[0052] Please note that the above-mentioned gain controlling stage 304 is just one possible embodiment, the scope of the present invention is not limited by the gain controlling stage. Any circuit that generates the gain controlling voltage Vy being proportional to ln(Ia/Ib-K3) can be used in the present invention. Wherein K3 is a constant, Ia corresponds to the first controlling voltage V1, and Ib corresponds to the second controlling voltage V2.

[0053] Please refer to equation 11, through the gain controlling stage 304, the relationship between the voltage gain Av of the amplifying stage 302, and the difference between V1 and V2, the gain is a simple exponential function, as

shown in Fig.6. Because there is no Vt term in equation 11, the voltage gain Av is not affected by the thermal voltage. That is the value of the voltage gain Av is independent of the thermal voltage. Additionally, in the above-mentioned embodiment, the amplifying stage has two input ends for receiving differential input voltage but only a single output end, however, the amplifying stage according to the present invention can also have two output ends for generating a differential output voltage.

[0054] In addition, the amplifying stage used with the present invention does not necessarily need to be as shown in Fig.1. Any circuit that has a voltage gain with a denominator containing a constant term and a simple exponential function can be used with the present invention.

[0055] Those skilled in the art will readily observe that numerous modifications and alterations of the device may be made while retaining the teachings of the invention. Accordingly, that above disclosure should be construed as limited only by the metes and bounds of the appended claims.